Phreatic Overgrowths on Speleothems (POS) from Mallorca, Spain: Updating forty years of research

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1. Introduction

Mallorca Island is internationally renowned as one of the classical sites for marine Pleistocene studies in Western Mediterranean basin (Hey, 1978; Pirazzoli, 1987; Zazo, 1999; Zazo *et al.*, 2003). Owing to a series of remarkable papers, started in the second half of the 20th century, an excellent record of high sea-stands is now available in the literature (Butzer & Cuerda, 1962; Butzer, 1975; Cuerda, 1975; Pomar & Cuerda, 1979). Besides the mentioned publications, additional investigations have recently been performed on Pleistocene beach deposits from Mallorca, using various geochronological techniques such as amino acid racemization, optical stimulated luminescence, and U-series radiometric dating of fossil mollusca (Hearty *et al.*, 1986; Hearty, 1987; Hillaire-Marcel *et al.*, 1996; Rose *et al.*, 1999).

On the other hand, an outstanding aspect of the Mallorcan's endokarst is the presence of sea level controlled phreatic crystallizations. This kind of deposits is commonly found in the subterranean pools of littoral caves, at current sea level (Pomar *et al.*, 1979; Tuccimei *et al.*, 2009). The main interest in these carbonate precipitates is that they record ancient higher and/or lower sea-stands, by means of horizontal alignments of water-table crystalline overgrowths in coastal caves of the island.

During the last decades, a new approach to the Mediterranean sea-level history has arisen from the interdisciplinary study of such Phreatic Overgrowths on Speleothems (POS) in the littoral caves of Mallorca (Figure 1). A comprehensive bibliographic revision on this topic is provided by Ginés (2000), whereas recent updated data sets are available in Tuccimei *et al*. (2006, 2010) and Dorale *et al*. (2010). The geomor-phological approach to these karst deposits has been fully supported by chronological information obtained from U-series datings of the POS samples. The data gathered altogether represent a very precise archive of glacioeustatic fluctuations during the

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Quaternary in the studied area. The eustatic curve for the time span between 150 and 60 ka BP is especially detailed.

Here we present the state-of-the-art on POS studies from littoral caves in Mallorca, with emphasis on their morphological, mineralogical, and crystallographic aspects as well as their significance in investigating sea-level history.

2. Investigations of Mallorcan POS: a four decades story

Examination of phreatic speleothems in littoral caves of Mallorca Island started in 1972, when striking bands of subaqueous crystallizations were observed in Cova de sa Bassa Blanca (Alcúdia) being tentatively credited to represent past Pleistocene sea stands (Ginés & Ginés, 1972). In fact, this kind of speleothem had been previously mentioned in earlier papers on Coves del Drac (Manacor), predicting their formation during some drowning events related to past elevations of the water table (Rodés, 1925; Joly, 1929; Colom *et al.*, 1957).

The first work on Mallorcan POS focused on correlating their elevation with the fossil beach sequences, abundant along the coasts of the island (Cuerda, 1975; Pomar &

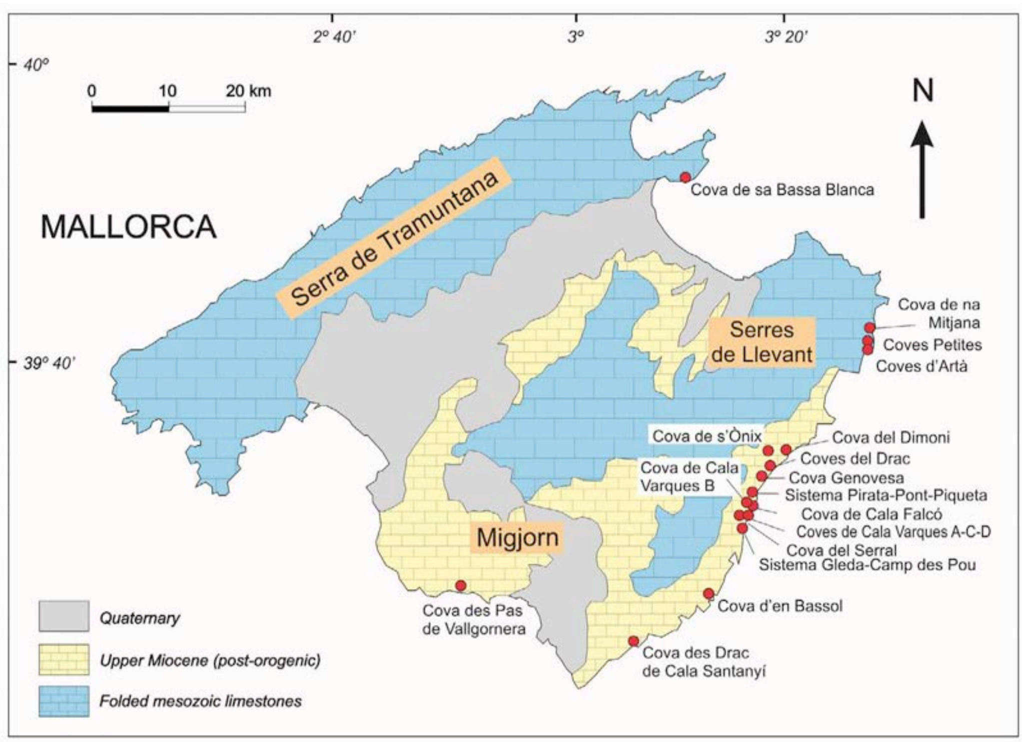


Figure 1. Location map of the most significant caves containing sea level controlled Phreatic Overgrowths on Speleothems (POS) along the coasts of Mallorca.

Cuerda, 1979). Using this approach, the phreatic speleothems bands, distributed from the current sea level (0 ASL) to +46 m ASL, were correlated to ancient coastlines encompassing the time span from the Last Interglacial to the Middle Pleistocene for the highest observed POS (Ginés, 1973; Ginés & Ginés, 1974; Ginés *et al*., 1975). Meanwhile, the precipitation of carbonates at present-day sea level was described in the form of floating calcite rafts (Pomar *et al.*, 1975) and bulky calcite overgrowths. Both of these speleothems develop within the current tidal range of the coastal cave pools (Pomar *et al.*, 1979). Early mineralogical and crystallographical studies on POS identified the presence of aragonite deposits, pointing out their potential paleoclimatic significance (Pomar *et al.*, 1976). All these aspects were internationally disseminated during the *8th International Congress of Speleology* held in Bowling Green (USA), in two papers dealing with the morphology and mineralogy of POS and, especially, to their potential as records of past sea levels (Ginés *et al*., 1981a, b). These investigations, that started from the Mallorcan speleological scene owing to the already cited works by A. Ginés and J. Ginés, very early were developed as a collaborative project within the *Universitat de les Illes Balears* (UIB), particularly with L. Pomar and subsequently with J.J. Fornós.

During the 1980s, a programme of U-series datings was commenced due to the interest and dedication of the late G.J. Hennig. Up to 16 U/Th ages on POS were performed at the *Niedersächsisches Landesamt für Bodenforschung* (Köln, Germany) by means of alpha-spectrometry techniques. The ages range from Holocene to older than 350 ka BP, including samples that clearly corresponded to the Last Interglacial (Hennig *et al*., 1981; Ginés & Ginés, 1989, 1993a, b, 1995). During these years, electron spin resonance (ESR) measurements were also conducted in order to obtain additional geochronological data on Mallorcan POS. This dating method was applied to a core drilled in the thick phreatic coatings covering the walls of Cova de sa Bassa Blanca (Maroto & Font, 1981; HADES, 1985). This publication also supplied 4 new U/Th ages of the core, and suggests that the complex sequence –including both phreatic and vadose crystallizations– was deposited over a long time span, ranging from 700 to 200 ka BP (Grün, 1985, 1986). More recently, stable isotope data were published in a paleoclimatic study of the same drilled core from Cova de sa Bassa Blanca (Csoma *et al*., 2006).

Between 1995 and 2000, a second U-series dating programme was conducted in collaborative research with the *Università Roma Tre* (Rome, Italy), under the leadership of Paola Tuccimei. More than 30 U/Th ages were published during this period, corresponding to POS paleolevels situated both above and below the current sea level (Tuccimei *et al*., 1997, 1998, 2000; Ginés *et al*., 1999, 2001a, b, 2002, 2004). The tasks of sampling the submerged phreatic speleothems were accomplished during important underwater exploration carried out by an extremely active and dedicated team of Mallorcan speleo-divers (Gràcia *et al*., 2007). Most of the U-series analyses resulting from this dating campaign were performed by means of alpha-counting techniques, with only a few obtained by thermal ionisation mass spectrometry (TIMS). The ages range between 67 ka and >350 ka BP, with over 16 dates corresponding to different substages of MIS 5. These allowed our team to reconstruct, for the first time, a detailed eustatic curve for western Mediterranean basin between 150 and 60 ka BP (Tuccimei *et al*., 2000; Ginés *et al*., 2003). The geochronological investigations carried out along this period were complemented with a few stable isotopes data on POS, meant to provide some preliminary paleoclimate information (Vesica *et al*., 2000). Furthermore, research on Mallorca's recent tectonics was evaluated in a paper that highlights the potential use of POS in structural geology studies (Fornós *et al*., 2002). A detailed revision on the knowledge about POS of Mallorca was included in the PhD dissertation of Ginés (2000). His work deals with the geomorphological aspects of Mallorca's littoral endokarst, emphasizing chronological aspects related to coastal caves. Some efforts were also directed towards the mineralogical, crystallographic, and textural description of different types of phreatic speleothems, generating a paper on this topic a few years later (Ginés *et al*., 2005). Finally, it is worth mentioning that the POS investigations were extended to Sardinia (Italy) in order to elucidate the tectonic situation of both islands in the frame of the Western Mediterranean basin (Tuccimei *et al*., 2003, 2007).

During the most recent decade, a third programme of radiometric investigation commenced on POS with a two-fold purpose: first, to obtain accurate U/Th ages by means of multi-collector inductively coupled plasma mass-spectrometry technique (MC-ICPMS) and second, to study in detail the Holocene POS. Over 47 mass-spectrometry datings were performed mainly at the laboratory of the Institute of Geology from the *University of Bern* (Switzerland) –owing to the collaboration of Jan Kramers and Igor M. Villa– as well as 12 additional dates completed by Bogdan P. Onac (*University of South Florida*) and Jeffrey A. Dorale (*University of Iowa*) who in the last years joined this research project. The recent research on subactual POS have two

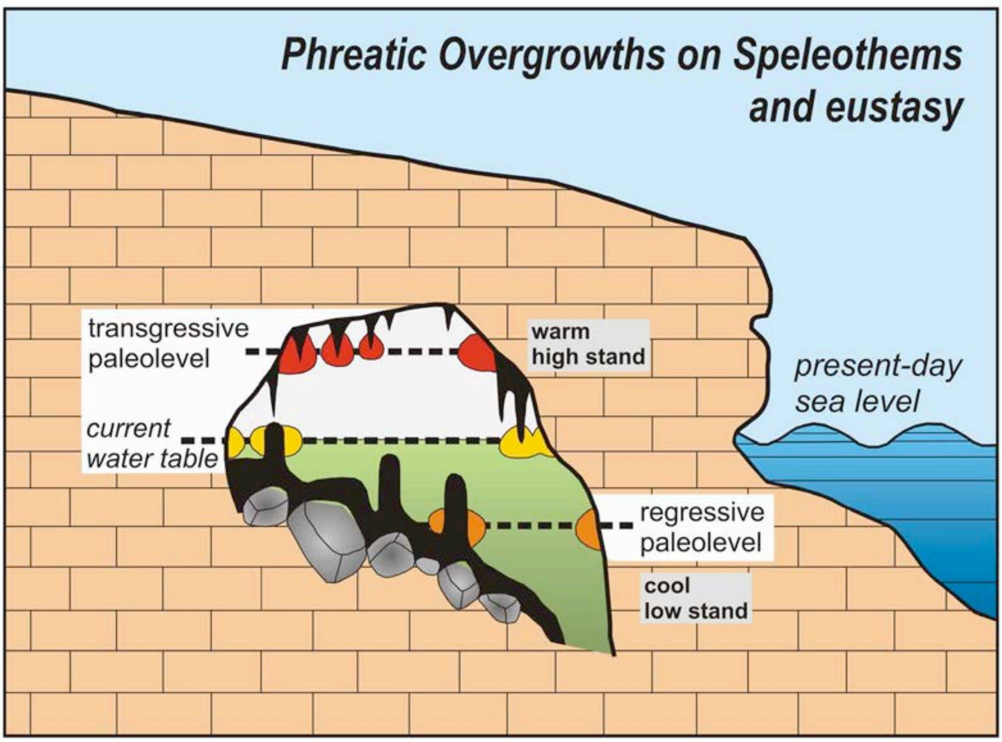


Figure 2. Sketch of a karstic littoral cave of Mallorca hosting present-day as well as ancient POS deposits. Broken lines represent the mean elevation attained by the ground water table during each recorded sea stand.

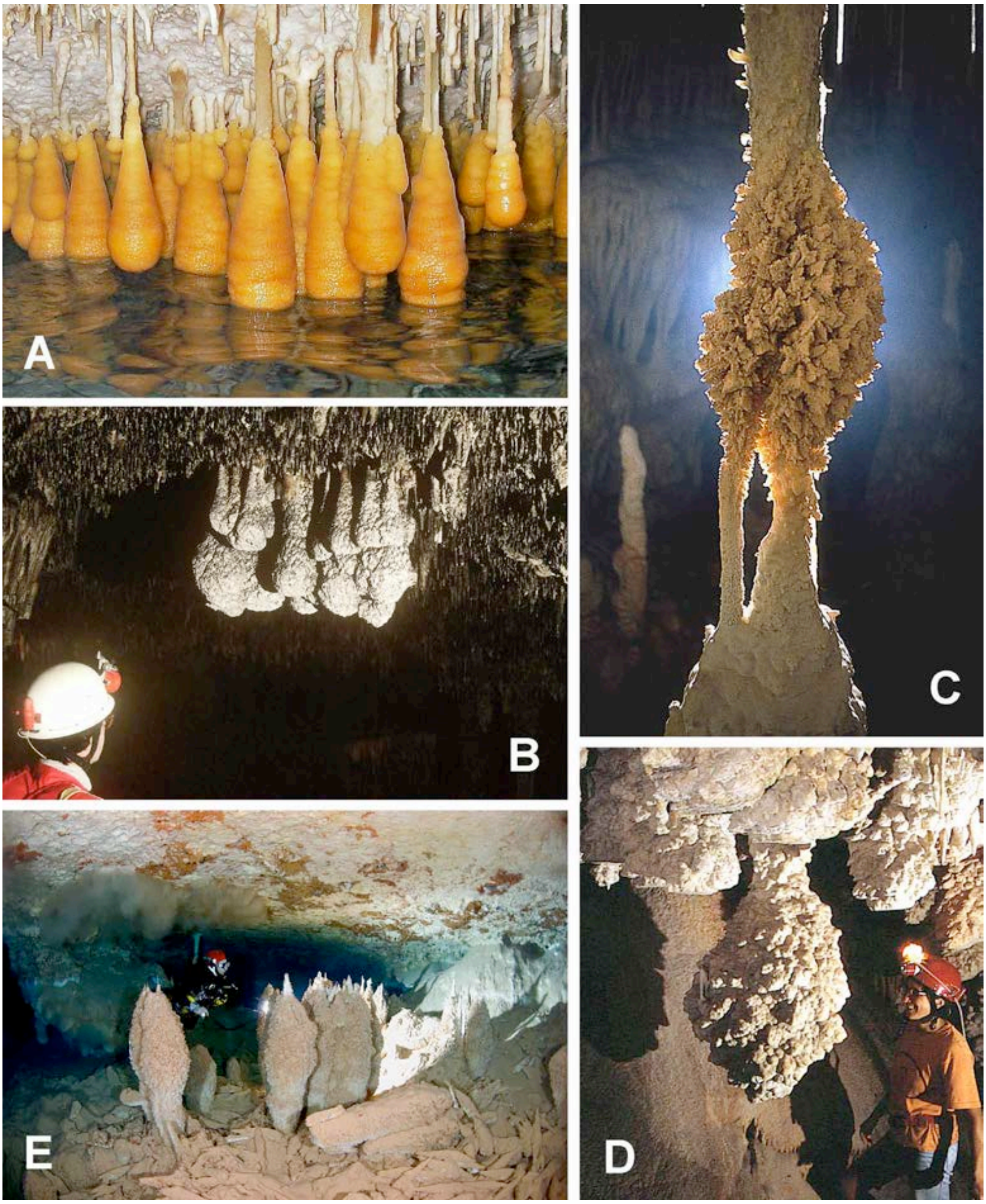


Figure 3. Photos of Phreatic Overgrowths on Speleothems (POS) from several Mallorcan caves. A: nice aragonite encrustations growing at the current water table in Cova des Pas de Vallgornera, Llucmajor. (Photo: A. Merino). B: group of POS crystallizations that record an ancient sea stand in Coves del Drac (Manacor), at an elevation of +4 m above the present-day sea level. (Photo: J. Ginés). C: spectacular calcite overgrowth corresponding to MIS 5e in Cova des Pas de Vallgornera (Llucmajor), located at an elevation of +2.6 m ASL (Photo: A. Merino). D: bulky macrocrystalline POS deposits from Cova de na Mitjana (Capdepera), recording a Middle Pleistocene high sea stand at +6 m ASL (Photo: J. Ginés). E: band of POS deposits corresponding to a regressive event, submerged in Cova de sa Gleda (Manacor) at a depth of –15 m ASL. (Photo: A. Cirer).

clear objectives: firstly, to confirm the presumed postglacial age of these deposits, as well as to supply new data on Holocene sea level in Mallorca (Tuccimei *et al*., 2009, 2010); and second, additional ^{14}C analyses were conducted on these postglacial precipitates (Tuccimei *et al*., 2011). Undoubtedly, the main achievement of this third dating programme is the generation of an accurate eustatic curve (for the Last Interglacial to Holocene times) based on all available U-series data on POS. The new dates, especially those falling between 150 and 60 ka BP, provide reliable information about sea level history during MIS 5 in Mallorca (Tuccimei *et al*., 2006), novel data on the MIS 5a high sea stand (Onac *et al*., 2006; Dorale *et al*., 2010), and on the glacial isostatic adjustments in the Western Mediterranean area (Tuccimei *et al*., 2012).

3. Phreatic Overgrowths on Speleothems (POS) from Mallorca Island

Karst caves are abundant along the southern and eastern coasts of Mallorca, particularly in the Upper Miocene post-orogenic carbonate rocks (Ginés, 1995: Ginés & Ginés, 2009). One of the most distinctive features of the coastal endokarst on Mallorca Island is the presence of extensive subterranean brackish pools. These ponds are currently flooding the lower parts of the caves, in elevational and hydrodynamic correspondence with present-day Mediterranean sea-level (Ginés & Ginés, 2007). The sea-level control over the littoral cave pools is evident since their surface undergoes daily fluctuations, related to minor tidal and/or barometric sea-level oscillations.

In this particular microenvironment, geochemically characterized by relatively elevated contents of chloride, sulfate, magnesium, and calcium, it is possible to observe freshly precipitated carbonates (crystalline overgrowths forming horizontal bands, floating calcite rafts, etc.) linked to the surface of these subterranean ponds (Pomar *et al*., 1976, 1979; Tuccimei *et al*., 2010). Just as the POS record the current sea-level position, ancient crystallizations of the same type –situated both above and below the present-day ±0 elevation datum– prove to be an excellent register of past sea-level (Figure 2), a fact documented in a number of papers (Ginés, 2000; Vesica *et al*., 2000; Fornós *et al*., 2002; Tuccimei *et al*., 2006; Dorale *et al*., 2010).

Generally speaking, the POS from Mallorcan littoral caves are crystalline coatings that define strictly horizontal bands. These carbonate encrustation develop along the cave walls, or over any suitable support (for example, common vadose speleothems) penetrating below the surface of the subterranean pools (Figure 3). The morphology of these coatings is bulky and its maximum thickness corresponds to the mean position of the water-table. As a rule, the thickest part of the overgrowth is located in the middle of the crystallizations belt, gradually decreasing upward and downward.

The belt-like form of POS deposits has a rather simple statistical explanation that relates to the position of the water table, where the maximum thickness occurs at the mean sea level during its growth period (Pomar *et al*., 1979). The aforementioned morphology develops when the POS inner support is always and continuously in contact with the fluctuating water table (i.e. columns, tall stalagmites and stalactites, or cave walls; case 1 in Figure 4). However, the overgrowth shape can be substantially different when POS develops on small stalactites –formed during sea-lowering events–

whose tips do not penetrate deep enough below the pool surface. In this situation, theprecipitation is abruptly truncated and flat-bottomed bulky overgrowths form (case 2, in Figure 4). The resulting appearance is simply due to the lack of the lowest part of the overgrowth.

The morphological variety of phreatic speleothems is enormous (Ginés & Ginés, 1974; Ginés *et al*., 2005). Very abundant and conspicuous are those globular forms described above. At the same time, some other forms are represented, but to a lesser extent, as for example the deposits of floating calcite and/or aragonite rafts, as well as cave cones produced by the accumulation of sunken floating rafts (Pomar *et al*., 1976; Ginés *et al*., 2005). These variegated phreatic crystallizations constrain (in a very noticeable manner) fully horizontal belts of encrustations, whose elevation correspondence with contemporaneous sea-level is the central to the present investigations, as earlier postulated by Ginés & Ginés (1974), Ginés *et al*. (1981a), and Pomar *et al*. (1987).

Currently up to 30 paleolevels of POS (ranging from +46 m ASL to –23 m below the current ±0 datum) have been recognized in Mallorcan caves (Ginés, 2000). Overall, the POS alignments that are localized at positive elevations record transgressive high-stands associated with interglacial or interstadial periods, whereas the speleothem bands or overgrowths situated below the current sea-level may correspond to regressive pulsations linked to glacial or stadial conditions. Referring briefly to the

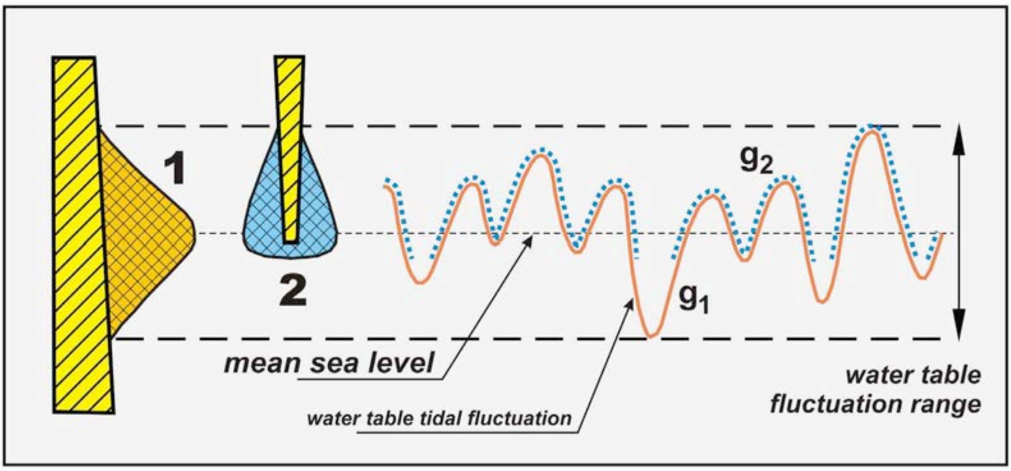


Figure 4. Schematic cross-view of phreatic carbonate encrustations (POS) developed over two different supports (after Tuccimei *et al.,* 2010). In case 1, POS develops on a support that is continuously in contact with the fluctuating water table (a stalagmitic column, for instance), originating a symmetric overgrowth with the maximum thickness corresponding to the more frequent position of the water table. In case 2 the crystallization develops over a stalactite, whose tip does not penetrate deep enough below the pool surface, producing an asymmetric flat-bottomed overgrowth. The solid (g1) and the dotted (g2) line are the growth histories of speleothems in case 1 and 2, respectively; note that g1 is coincident with the full sea level fluctuation range, whereas g2 only records the upper part of that range.

mineralogy of POS, it is possible to assess how calcite and (in a lesser extent) aragonite are predominant in these deposits. Aragonite crystallizations occur particularly in some paleolevels located above the current sea-level, as well as Holocene POS in the Cova des Pas de Vallgornera. The aragonitic mineralogy likely has paleoclimatic significance (Pomar *et al*., 1976; Ginés *et al*., 1981b; Vesica *et al*., 2000), being present in samples belonging to warmer substages of MIS 5. Aragonite encrustations originate characteristic smooth coatings, whereas calcite POS show macrocrystalline textures with rough surfaces. All these mineralogical and crystallographic aspects will be discussed in a further section.

4. Methodology

The first step in the present research was the identification of phreatic speleothem bands, which are clear recorders of sea-level. Investigations were formerly centered in eastern and southern coasts of Mallorca, areas with abundant coastal endokarstic phenomena. The alignments of POS recognized inside the caves were extensively sampled with selective criteria (in particular those forms developed on stalactites, that are of easier collection without drilling equipment), being at the same time topographically determined their elevation with respect to the current ±0 ASL datum. Exploration of caves has required the use of conventional speleological and the more specialized scuba-diving techniques in the cave pools for sampling the lower sea-level stands.

The collected samples have been radiometrically dated by means of the U-series method. The first programmes of U/Th datings were carried out by alpha-counting, at the laboratories of *Niedersächsisches Landesamt für Bodenforschung* (Köln, Germany) and *Università Roma Tre* (Rome, Italy). Nevertheless the major bulk of datings were performed in the last decade by mass-spectrometry techniques (TIMS and MC-ICPMS), mainly at the *University of Bern* laboratory (Bern, Switzerland). Average errors of the obtained ages are respectively about 3% (1s) for alpha-counting and 1.5% (2s) for TIMS and MC-ICPMS analyses (see additional technical details in Vesica *et al*., 2000 and Tuccimei *et al*., 2006). The availability of reliable chronological data concerning the sampled POS should potentially contribute to the reconstruction of Mediterranean sea-level history during the last 500 ka, age that constitutes the applicability limit of the U-series radiometric techniques. Additional geochronological tasks have included ^{14}C dating of Holocene samples (Tuccimei *et al*., 2011), as well as ESR measurements of some ancient POS paleolevels (Grün, 1986).

Mineralogical and crystallographic investigation of the samples involved XRD analyses as well as optical and scanning electron microscopy observations. The aim of such studies was to evaluate the paleoclimatic information archived within these speleothems. Particular attention would be focused on the environmental controls of aragonite precipitation in the littoral phreatic zone. Finally, C and O stable isotope analyses were performed on the growing layers of some samples, in order to gather additional paleoclimatic data at the time these carbonate deposits were precipitated (Vesica *et al*., 2000; Csoma *et al*., 2006).

5. Results of U/Th dating and proposed eustatic curve

The core of these researches is represented by the results generated over several dating programmes (U/Th method), starting in the eighties of the last century (Hennig *et al.*, 1981; Ginés & Ginés, 1989, 1993a) and until the present (Tuccimei *et al.*, 2000, 2006, 2010; Dorale *et al.*, 2010). From a total of 97 U-series ages ranging from 0.6 ka to >350 ka BP (44 based on alpha-counting techniques and 53 obtained by means of mass-spectrometry measurements), up to 55 dates cluster between 60 and 150 ka BP. The obtained data provide accurate elevations of sea level high- and low-stands both during the Holocene and over the MIS 5 and 4; these data are discussed below. The acquisition of absolute ages based on the investigated POS paleo sea-levels, coupled with the precise determination of their elevation, have allowed us to tentatively reconstructing an eustatic curve for the Western Mediterranean basin covering the time period between the Middle Pleistocene until present.

5.1. Dating of Holocene POS

The investigations on POS deposits (Figure 5) that are presently located around the current sea level were directed towards two different goals: first, it was necessary to check the postglacial age of these deposits, in order to confirm the potentiality of POS as recorders of the subactual sea level; second, the obtained results must provide precise data on Holocene sea level in the Western Mediterranean basin.

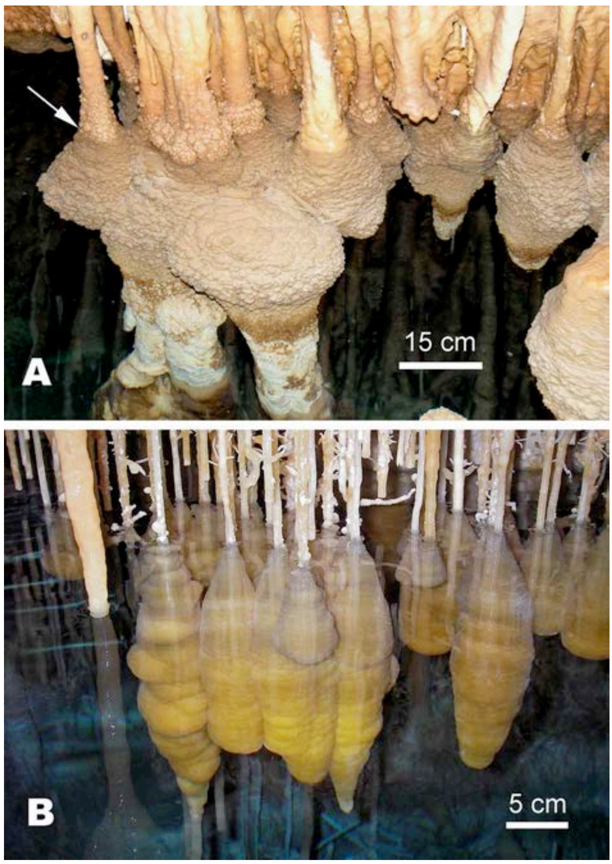


Figure 5.
Carbonate crystallizations occurring at the surface of brackish pools in Mallorcan caves.
A: Calcite belt of phreatic over-growths on speleothems (POS) in Cova de Cala Varques A (Manacor); white arrow emphasize water table position when the picture was taken, which was higher than mean sea level. (Photo: B.P. Onac).
B: Aragonite belt of POS from Cova des Pas de Vallgornera (Llucmajor); the thickest part of the overgrowth band corresponds to the mean sea level. (Photo: A. Merino).

Two caves in Eastern Mallorca were chosen for this purpose. Cova de Cala Varques A (Manacor municipality) is an outstanding site located only a few metres away from the coastline, and is characterized by the presence of bulky calcite POS encrustations developed all along the margins of extensive brackish pools (Figure 5a). On the other hand, Cova des Pas de Vallgornera (Llucmajor) is a vast littoral cave system with more than 67 km of passages, showing prominent aragonite POS located at the surface of the underground brackish pools (Figure 5b); the artificial cave entrance is about one hundred metres from the sea cliff.

Fourteen samples were drilled from speleothem VA-D1 (Cova de Cala Varques A), two of them from the inner vadose stalagmite and twelve from the phreatic overgrowth. From VL-D3 speleothem (Cova des Pas de Vallgornera), five samples were obtained from the aragonite phreatic encrustation. The samples were drilled along transects transverse or parallel to the POS growth axis (Figure 6). The VA-D1 overgrowth consists of high-Mg calcite, crystallized as mm-size rhombohedral crystals that are growing in a parallel or dendritic pattern, whereas VL-D3 sample is composed of 20 μm wide and 1 mm long acicular aragonite crystals, arranged in 0.3-1 mm thick growth layers.

The age data (Table I) show that POS from the two caves grew approximately the same time, although there is a slight shift at the beginning and interruption of deposition. In particular, calcite precipitation at Cova de Cala Varques A took place from about 2.8 to 1.1 ka BP, whereas the aragonite deposition in Cova des Pas de Vallgornera occurred from about 2.0 to 0.6 ka BP (Tuccimei *et al.*, 2009, 2010). Subaerial calcite deposition in vadose conditions was active between 18.3 and 7.7 ka BP, in agreement with the younger phreatic overgrowth. In both cases, the ages of phreatic

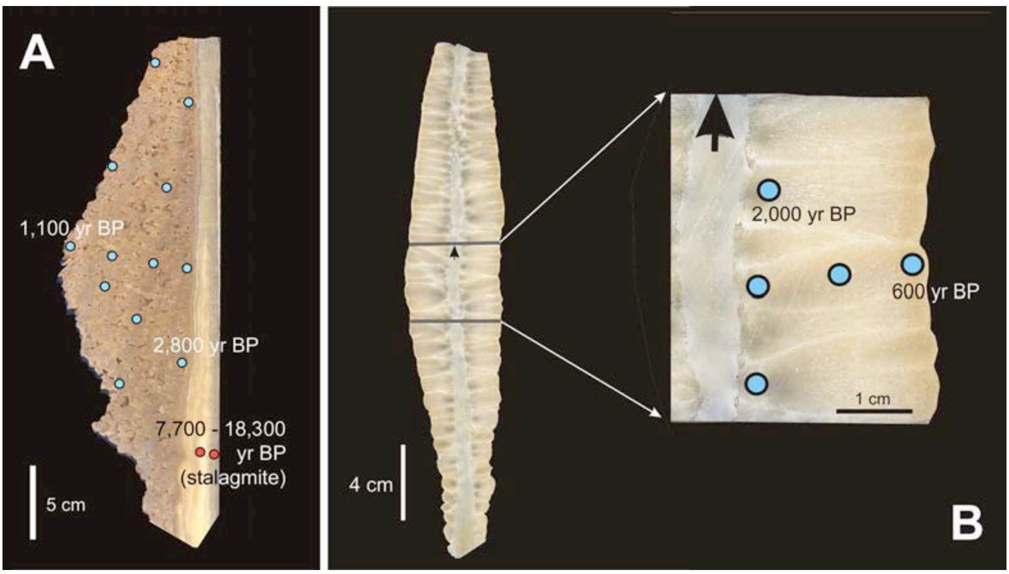


Figure 6. A: Location of samples drilled on speleothem VA-D1 (Cova de Cala Varques A). B: General cross-view of speleothem VL-D3 (Cova des Pas de Vallgornera) and location of the drilled samples. In both cases, the most illustrative U/Th ages are labeled over the pictures.

Table I. U/Th datings of Holocene POS samples, collected at the present-day sea level in two Mallorcan coastal caves.

Cave	Sample	U (ppb)	$^{234}U/^{238}U$	$^{230}Th/^{232}Th$	$^{230}Th/^{238}U$	$(^{230}Th / ^{238}U)_{corr}$ *	*Age-C* * (*ka* ± 2σ)	*Age-I* ** (*ka* ± 2σ)
Cova de Cala Varques A	VA-D1-1	406	1.632 ± 0.001	2.52 ± 0.04	0.0460 ± 0.0003	0.0310 ± 0.0065	**2.08 ± 0.44**	**2.80 ± 0.04**
	VA-D1-9	473	1.710 ± 0.001	6.90 ± 0.05	0.0450 ± 0.0003	0.0397 ± 0.0023	**2.55 ± 0.15**	
	VA-D1-2	306	1.457 ± 0.001	4.71 ± 0.06	0.0309 ± 0.0003	0.0255 ± 0.0023	**1.92 ± 0.18**	**2.30 ± 1.40**
	VA-D1-5	304	1.462 ± 0.001	2.93 ± 0.04	0.0341 ± 0.0004	0.0244 ± 0.0042	**1.83 ± 0.31**	
	VA-D1-6	316	1.494 ± 0.001	6.06 ± 0.04	0.0312 ± 0.0002	0.0270 ± 0.0018	**1.98 ± 0.14**	
	VA-D1-7	281	1.442 ± 0.001	5.33 ± 0.08	0.0287 ± 0.0004	0.0242 ± 0.0020	**1.85 ± 0.15**	
	VA-D1-8	279	1.425 ± 0.001	2.84 ± 0.03	0.0295 ± 0.0003	0.0209 ± 0.0037	**1.60 ± 0.29**	
	VA-D1-3	294	1.416 ± 0.001	7.12 ± 0.08	0.0212 ± 0.0003	0.0188 ± 0.0011	**1.45 ± 0.09**	**1.50 ± 0.07**
	VA-D1-10	294	1.424 ± 0.001	4.93 ± 0.04	0.0224 ± 0.0001	0.0186 ± 0.0016	**1.43 ± 0.13**	
	VA-D1-4	310	1.415 ± 0.001	0.471 ± 0.006	0.0580 ± 0.0006	-0.0521	negative age	**1.10 ± 0.50**
	VA-D1-11	336	1.384 ± 0.002	0.362 ± 0.005	0.1221 ± 0.0015	-0.2307	negative age	
	VA-D1-12	322	1.435 ± 0.001	0.757 ± 0.010	0.0254 ± 0.0003	-0.0032	negative age	
	VA-D1-13 +	*270*	*1.170 ± 0.001*	*7.00 ± 0.06*	*0.2022 ± 0.0015*	*0.1821 ± 0.0089*	***18.30 ± 1.0***	
	VA-D1-14 +	*106*	*1.160 ± 0.001*	*17.4 ± 0.2*	*0.0829 ± 0.0001*	*0.0792 ± 0.0016*	***7.70 ± 0.20***	
Cova des Pas de Vallgornera	VL-D3-1	8829	1.480 ± 0.002	271 ± 2	0.0262 ± 0.0002	0.0261 ± 0.0002	**1.94 ± 0.01**	
	VL-D3-2	7396	1.478 ± 0.002	69.3 ± 0.4	0.0250 ± 0.0002	0.0247 ± 0.0002	**1.84 ± 0.02**	
	VL-D3-3	8139	1.475 ± 0.001	510 ± 3	0.0264 ± 0.0002	0.0271 ± 0.0001	**2.02 ± 0.01**	
	VL-D3-4	8217	1.487 ± 0.001	457 ± 3	0.0183 ± 0.0001	0.0183 ± 0.0001	**1.35 ± 0.01**	
	VL-D3-5	8015	1.503 ± 0.002	145 ± 1	0.0084 ± 0.0002	0.0084 ± 0.0002	**0.61 ± 0.01**	

\+ Cross indicates subsamples from the inner vadose support
* $(^{230}Th/^{238}U)_{corr}$ and *Age-C* have been corrected for an initial $^{230}Th/^{232}Th$ ratio of 0.85 ± 0.36
** *Age-I* is calculated from the intercept of $^{232}Th/^{238}U$ vs $^{230}Th/^{238}U$ isochron diagrams for VA-D1 samples (see details in Tuccimei et al., 2010)

encrustations are stratigraphically consistent, suggesting the chemical system probably remained closed since deposition and no leaching or preferential dissolution occurred. The time shift and mineralogical differences could be explained by changes in the local chemical conditions of the pool waters (Pazzelli, 1999), which could be related to the fact that the two caves sit at different distances from the coastline. It is worth noting that the extent of POS deposition represents a minimum time interval for sea stand at the current elevation, since the chemical properties of phreatic waters can change during a given sea stand, causing the POS growth to cease. The fine-scale spatial distribution of ages among VA-D1 subsamples also suggests a possible slight rise of sea level (~5-10 cm) during its precipitation.

Detailed information regarding the methodology and the results of MC-ICPMS dates performed on these samples is available in Tuccimei *et al*. (2010). Special attention is given to detrital Th corrections applied for each speleothem, according to their different mineralogy, U contents, and isotopic activity ratios. Stable isotope analyses provided in that paper document relatively high $\delta^{18}O$ (from -4.2 to -3.4‰ VPDB) and $\delta^{13}C$ (from -3.2 to -2.2‰ VPDB) values if compared with those of the vadose stalactite ($\delta^{18}O$ from -5.6 to -4.9‰ VPDB; $\delta^{13}C$ from -7,9 to -5.9‰ VPDB). This is likely due to different proportions in which sea water and groundwaters mix and also depends on the distance between the cave pools and the coastline.

The coherent ages obtained demonstrate that POS are excellent recorders of postglacial sea level, being readily datable by U-series methods. This fact allows to foresee POS as useful indicators of past sea stands, especially when these precipitates are found in coastal caves at different elevations above or below the present sea level, as is the case in Mallorca's littoral caves.

Regarding the Holocene sea level history, it is worth mentioning some complementary archeological evidence from a cave in the studied area. In the entrance chamber of Cova Genovesa (a cave located only a few kilometres away from Cova de Cala Varques A), a drowned prehistoric construction lies 1 m below the present-day water table (Gràcia *et al*., 2003). This archeological vestige consists of a stone-built passage that, at the time of its construction, enabled users to cross the first chamber pool without getting wet; it is a 7 m long stepping stones path, composed of at least 14 deliberately aligned rock blocks, some of them with the major axis greater than 1 m. The occurrence of a past sea level at a depth of ~ –1 m is also strengthened by the presence of a horizontal coloration mark, observable at both sides of the construction, as well as along the submerged cave walls. Scarce pottery findings date back to Bronze Age (Gràcia *et al*., 2003) and chronologically constrain the use of the cave to the final stage of the Navetiform culture (3.7 to 3.0 ka BP). Combining archeological data and U/Th chronology of POS (Tuccimei *et al*., 2009, 2010), it is possible to recognize a relative low stand at about –1 m, around 3.7-3.0 ka BP, followed by a rise of sea level, with a successive stabilization at the present elevation since ca. 2.8 ka BP.

5.2. Dating of Pleistocene POS

The early U/Th dating programmes conducted by means of alpha-spectrometry on phreatic speleothems from Mallorca –collected both above and below the current sea level– yielded ages from about 63 ka to >350 ka BP (Hennig *et al*., 1981; Ginés & Ginés, 1989, 1993a; Tuccimei *et al*., 1998, 2000; Ginés *et al*., 2003). Apart from a few POS samples presumably corresponding to MIS 7 or even earlier (MIS 9 or 11), the vast majority of ages were in the range 150-60 ka BP providing valuable information on sea level history during MIS 5. Additional research taking advantage of recent mass-spectrometry techniques have allowed lately constraining a more detailed and accurate Upper Pleistocene eustatic curve for the Western Mediterranean basin (Tuccimei *et al*., 2006; Dorale *et al*., 2010), which will be conveniently discussed in the next sections. In total, more than 50 phreatic speleothems collected in 17 littoral caves of Mallorca (Figure 1) were investigated over the last four decades.

5.2.1. High and low sea level stands around MIS 5 documented by dating POS

The ages of phreatic overgrowths, dated by means of TIMS and MC-ICPMS techniques, range from 143.6 to 77.8 ka BP, covering the entire Last Interglacial interval (Table II). The following three high stand episodes (i.e., past sea levels located at elevations higher than present-day) have been detected. The height, age, and duration of these high stands are listed below from the oldest to the youngest:

- a first stand (MIS $5e_2$) at +1.5/+3 m ASL, with possible initiation as early as 140.8, but not later than 135.2 ka BP. The termination of this episode can be set somewhere between 131 and 126 ka BP, resulting in a possible duration of 4.2 to 14.8 ka.

Table II. U/Th ages of Upper Pleistocene POS samples from caves along the eastern and southern Mallorcan coasts.

Cave	Sample	Height *a.s.l.* (m)	U (ppb)	^{234}U / ^{238}U	$(^{234}U/^{238}U)_0$	$^{230}Th/^{232}Th$	^{230}Th / ^{234}U	Age (*ka* ± 2*σ*)
Cova del Dimoni	DI-D1-1 # ***a***	+2.5	2531 ± 7	1.273 ± 0.002	1.372 ± 0.003	236 ± 2	0.654 ± 0.004	**109.9 ± 1.1**
	DI-D1-2 # ***a***	+2.5	1254 ± 5	1.087 ± 0.001	1.122 ± 0.014	5231 ± 62	0.670 ± 0.003	**118.4 ± 0.9**
	DI-D3 # ***a***	+2.5	2050 ± 6	1.192 ± 0.001	1.265 ± 0.001	2834 ± 55	0.664 ± 0.003	**114.2 ± 0,9**
	CDD-1 * ***b***	+1.5	1191 ± 19	1.178 ± 0.003	1.223 ± 0.038	18814	0.530 ± 0.004	**80.4 ± 0,6**
	CDD-2 * ***b***	+1.5	1186 ± 18	1.177 ± 0.027	1.222 ± 0.034	17160	0.530 ± 0.003	**80.7 ± 0,5**
Coves del Pirata	PI-D1 # ***a***	+2.1	300 ± 1	1.649 ± 0.006	1.945 ± 0.010	1681 ± 20	0.751 ± 0.006	**133.0 ± 1.9**
Cova de Cala Falcó	FA-D3-4 # ***a***	+1.9	3976 ± 11	1.589 ± 0.001	1.743 ± 0.002	4236 ± 81	0.551 ± 0.004	**82.3 ± 0.8**
	CCF-1 * ***b***	+1.6	208 ± 23	2.113 ± 0.009	2.397 ± 0.011	2410	0.551 ± 0.002	**80.4 ± 0.5**
	CCF-2 * ***b***	+1.6	202 ± 21	2.137 ± 0.012	2.431 ± 0.015	990	0.556 ± 0.002	**81.1 ± 0.5**
Cova de Cala Varques A	CCVA-1 * ***b***	+1.3	110 ± 22	1.377 ± 0.069	1.476 ± 0.086	9077	0.545 ± 0.002	**82.0 ± 0.6**
	CCVA-2 * ***b***	+1.3	121 ± 18	1.379 ± 0.055	1.478 ± 0.069	5599	0.544 ± 0.002	**81.7 ± 0.5**
Cova de Cala Varques B	VB-D2 # ***a***	+1.4	445 ± 1	1.476 ± 0.003	1.643 ± 0.005	133 ± 1	0.557 ± 0.004	**84.2 ± 1.0**
	VB-D3 * ***a***	-14.0	680 ± 2	1.881 ± 0.020	2.256 ± 0.028	320 ± 14	0.735 ± 0.007	**125.0 ± 2.0**
	VB-D5 # ***a***	-16.5	786 ± 2	1.822 ± 0.003	2.169 ± 0.005	891 ± 11	0.730 ± 0.003	**124.7 ± 0.9**
	CCVB * ***b***	+1.3	101 ± 21	1.376 ± 0.017	1.473 ± 0.021	418	0.541 ± 0.005	**80.8 ± 1.0**
Cova des Serral	SE-D2 # ***a***	+1.5	198 ± 1	1.521 ± 0.009	1.752 ± 0.013	591 ± 5	0.736 ± 0.005	**130.2 ± 1.6**
Cova de sa Gleda	GL-D1 # ***a***	-15.0	412 ± 1	1.949 ± 0.004	2.185 ± 0.005	201 ± 2	0.540 ± 0.004	**78.6 ± 0.8**
	GL-D2 # ***a***	-14.0	505 ± 1	1.968 ± 0.004	2.450 ± 0.009	242 ± 2	0.796 ± 0.005	**143.4 ± 1.6**
	GL-D3 # ***a***	-17.5	454 ± 1	1.931 ± 0.007	2.210 ± 0.009	336 ± 3	0.606 ± 0.004	**92.7 ± 0.9**
	GL-D5 * ***a***	-16.0	385 ± 1	2.094 ± 0.026	2.364 ± 0.032	230 ± 11	0.539 ± 0.004	**77.8 ± 0.8**
	GL-D6 # ***a***	-17.0	614 ± 2	1.931 ± 0.005	2.227 ± 0.008	671 ± 6	0.628 ± 0.005	**97.7 ± 1,1**
	GL-D7 # ***a***	-13.5	272 ± 2	1.667 ± 0.003	1.903 ± 0.008	42 ± 1	0.661 ± 0.022	**107.4 ± 2,8**
	GL-D8 # ***a***	-20.5	375 ± 1	1.840 ± 0.003	2.069 ± 0.005	43 ± 0.4	0.571 ± 0.011	**85.4 ± 0,9**
Cova d'en Bassol	PS-D2 * ***a***	-10.5	212 ± 1	1.611 ± 0.016	1.810 ± 0.020	45 ± 2	0.630 ± 0.005	**100.0 ± 1.0**
	PS-D5 # ***a***	-18.0	152 ± 1	1.858 ± 0.017	2.114 ± 0.022	157 ± 1	0.604 ± 0.008	**92.6 ± 1.8**
Cova des Pont	PO-D2 # ***a***	+2.1	347 ± 1	1.381 ± 0.003	1.539 ± 0.005	529 ± 9	0.704 ± 0.006	**122.7 ± 1.9**
Cv. Drac Cala Santanyí	CS-D3 # ***a***	-17.0	325 ± 1	1.365 ± 0.003	1.466 ± 0.004	25 ± 0.2	0.563 ± 0.004	**86.3 ± 0.9**
Cova Genovesa	GE-D1 # ***a***	+2.0	179 ± 1	1.102 ± 0.003	1.151 ± 0.004	59 ± 0.9	0.729 ± 0.007	**138.0 ± 2.8**
	GE-D2 # ***a***	-13.0	244 ± 1	1.233 ± 0.005	1.349 ± 0.009	38 ± 0.4	0.756 ± 0.012	**143.6 ± 4.6**
	GE-D3 # ***a***	-19.5	349 ± 1	1.731 ± 0.003	1.965 ± 0.006	72 ± 0.9	0.571 ± 0.004	**85.9 ± 1.0**
Cova de s'Ònix	OX-D1 # ***a***	+3.0	254 ± 1	1.443 ± 0.002	1.637 ± 0.005	37 ± 0.5	0.727 ± 0.008	**128.5 ± 2.5**
Cova des Pas de Vallgornera	CPV-1 * ***b***	+1.6	156 ± 30	1.325 ± 0.019	1.408 ± 0.024	31537	0.535 ± 0.003	**80.1 ± 0.5**
	CPV-2 * ***b***	+1.6	144 ± 28	1.329 ± 0.021	1.413 ± 0.026	34757	0.536 ± 0.002	**80.1 ± 0.5**
	CPV-B8 * ***b***	+1.6	119 ± 18	1.391 ± 0.016	1.492 ± 0.020	1812	0.541 ± 0.002	**81.0 ± 0.5**
	CPV-B6 * ***b***	+2.6	108 ± 20	1.141 ± 0.013	1.198 ± 0.018	1892	0.683 ± 0.003	**120.6 ± 0.9**
	CPV-B9 * ***b***	+2.6	122 ± 14	1.173 ± 0.012	1.240 ± 0.017	1151	0.671 ± 0.002	**116.2 ± 0.6**

\# MC-ICPMS   * TIMS
a data from Tuccimei et al. (2006)   ***b*** data from Dorale et al. (2010)

– a second stand (MIS $5e_1$), apparently longer than the first, at +2.5 m ASL, begun between 124.6 and 120.8 ka BP and ended sometimes between 111 and 108.8 ka BP, hence lasting 9.8 to 15.8 ka.

– a third short-lived stand (MIS 5a) was documented at +1.3 to +1.9 m ASL; the starting dates cluster between 85.2 and 82.5 ka BP. The demise of this high stand event was anywhere between 81.5 and 79.5 ka BP, resulting in its possible duration of 1 to 5.7 ka.

At least six low stand episodes (i.e., past sea levels found at elevations lower than the current sea level) have been documented, two of which at the MIS 6/MIS 5e and MIS 5a/MIS 4 transitions. The other four low stands fall within MIS 5. All six episodes are listed below from the oldest to the youngest:

- a first low stand is ~ –14/–13 m ASL and coincides with the MIS 6/MIS 5e transition, at ~ 143.5 ka BP.

- a second stand with a maximum depth of –16.5 m ASL was documented within MIS 5e, around 125 ka BP.

- a third stand at –13.5 m ASL (~107.4 ka BP) was tentatively correlated with MIS 5d.

- a fourth sea level stabilisation at –10.5 m ASL occurred around 100 ka BP (MIS 5c?) between the proposed MIS 5d paleolevel and the next recorded low sea stand at about –17 m ASL.

- a fifth low stand consisting of two main events: a first sea level stabilisation at –18/–17 m ASL from about 97.7 to 92.6 ka BP, and a second low stand at –20.5/–19.5 m ASL around 85.9 to 85.4 ka BP. The POS record for this interval, roughly corresponding to MIS 5b, remains open for different interpretations.

- a sixth low stand at the MIS 5a/MIS 4 transition was identified at –16/–15 m ASL and around 78.6 to 77.8 ka BP.

This detailed succession of Upper Pleistocene high and low sea stands, documented by the Mallorcan POS record, allows the construction of an eustatic curve for the Western Mediterranean encompassing the chronological and elevation data supplied by these crystallizations.

5.2.2. Comparison between mass-spectrometry and alpha-counting U/Th dating

High precision MC-ICPMS and TIMS data presented in the paragraphs above can be compared with previous alpha-counting derived ages (Table III) as discussed in Tuccimei *et al.* (2006). It is worth noting that the average errors associated to alpha-counting, and quoted as 2σ, ranged from 5 to 15%, while those obtained from mass-spectrometry measurements are generally around 1% or better. This implies that the time interval associated to ages of 100 ka for example is reduced from 10 ka (alpha-counting) to 1 ka (mass-spectrometry). This is crucial in the process of generating a detailed sea level changes curve.

By comparing the age results obtained by means of MC-ICPMS and TIMS (Tuccimei *et al.*, 2006) with those produced by alpha-counting (Tuccimei *et al.*, 1998, 2000; Ginés *et al.*, 2003), one can observe that both data always agree within the error range (quoted as 2σ), supporting the accuracy of the U/Th ages used for the construction of the proposed eustatic curve. Only in a single case (sample DI-D3), the mass-spectrometry age has lead to a different interpretation of the POS record, suggesting the absence of carbonate deposits that could document a MIS 5c high stand.

5.2.3. Sea level curve for the Last Interglacial

If chronological data from emergent and submerged POS are plotted versus their elevation with respect to present sea level (Figure 7), a tentative eustatic curve for the Last Interglacial in Mallorca can be generated (Tuccimei *et al.*, 2006) with accuracy greater than other approaches based on conventional geomorphological records (i.e., fossil beaches with diagnostic faunal content).

According to our findings, Western Mediterranean sea level reached approximately the same elevations (~+1.5/+2.5 m ASL) during the past high stands recorded in correspondence with MIS 5a and 5e ($5e_1$ and $5e_2$).

In particular, evidence of MIS 5a and 5e high stands within a few metres above sea level have been found in tectonically stable areas by Ultzega & Hearty (1986), Riccio *et al.* (1999) and Belluomini *et al.* (2002) in Sardinia and Southern Italy and by Ludwig *et al.* (1996), Neumann & Hearty (1996), Hearty (1998), and Muhs *et al.* (2003), along the US Atlantic coasts.

The age of 143.4 ka BP for sample GL-D2 located at 14 m below present sea level, along with the estimated commencement of the high stand correlated to early MIS 5e (i.e., 140.8-135.2 ka BP; see Table II), are consistent with the hypothesis of a sea rise at

Table III. Comparison between mass spectrometric (MC-ICPMS and TIMS) and alpha-counting ages of POS from Mallorca.

Sample	*Cave*	*Height* (m a.s.l.)	***Age (ka ± 2σ)*** Tuccimei et al., 2006	***Age (ka ± 2σ)*** previous references
GL-D5	Cova de sa Gleda	–16.0	**77.8 ± 0.8** [b]	78.0 ± 7.2 [c, 2]
GL-D1	Cova de sa Gleda	–15.0	**78.6 ± 0.8** [a]	76.2 ± 3.6 [c, 2]
FA-D3-4	Cova de Cala Falcó	+1.9	**82.3 ± 0,8** [a]	83.9 ± 5.0 [b, 1]
VB-D2	Cova de Cala Varques B	+1.4	**84.2 ± 1.0** [a]	83.4 ± 5.1 [b, 1]
CS-D3	Cova des Drac de Cala Santanyí	–17.0	**86.3 ± 0.9** [a]	79.6 ± 6.0 [c, 2]
PS-D5	Cova d'en Bassol	–18.0	**92.6 ± 1.8** [a]	98.0 ± 12.0 [c, 2]
GL-D3	Cova de sa Gleda	–17.5	**92.7 ± 0.9** [a]	91.4 ± 4.8 [c, 2]
PS-D2	Cova d'en Bassol	–10.5	**100.0 ± 1.0** [b]	100.0 ± 14.0 [c, 2]
DI-D1-1	Cova del Dimoni	+2.5	**109.9 ± 1.1** [a]	112.9 ± 11.6 [c, 1]
DI-D3	Cova del Dimoni	+2.5	**114.2 ± 0.9** [a]	107.9 ± 5.7 [c, 1]
DI-D1-2	Cova del Dimoni	+2.5	**118.4 ± 0.9** [a]	119.7 ± 10.0 [c, 1]
VB-D5	Cova de Cala Varques B	–16.5	**124.7 ± 0.9** [a]	125.6 ± 8.4 [c, 2]
VB-D3	Cova de Cala Varques B	–14.0	**125.0 ± 2.0** [b]	125.0 ± 16.0 [c, 2]
SE-D2	Cova des Serral	+1.5	**130.2 ± 1.6** [a]	121.3 ± 5.6 [c, 1]
PI-D1	Coves del Pirata	+2.1	**133.0 ± 1.9** [a]	130.4 ± 14.0 [c, 1]
GL-D2	Cova de sa Gleda	–14.0	**143.4 ± 1.6** [a]	147.4 ± 24.0 [c, 2]

[a] MC-ICPMS ages [b] TIMS ages [c] Alpha-counting ages
[1] data from Vesica et al. (2000) [2] data from Ginés et al. (2003)

the MIS 6 to MIS 5 transition, much earlier than the insolation maximum in the northern hemisphere centered ~128 ka ago (Winograd *et al.*, 1996). Shopov *et al.* (1998) report an increase in solar insolation occurred ~139 ± 5 ka BP and attribute it to a cycle of solar luminosity, with duration of 11.5 ka, superposed on the orbital variations curve. In addition, it is worth noting that the average duration estimated for the MIS $5e_2$ high stand is 9.5 ka, in agreement with the estimated length of the referred solar activity cycle. This suggests that the solar luminosity contribution to the global insolation curve may be underestimated.

During MIS 5e (i.e., 138 to 110 ka BP), two high sea stands separated by a brief low stand episode have been identified (Figure 7). The same marine regression within the Last Interglacial was recognized in Mallorca Island (Hillaire-Marcel *et al.*, 1996) and other geographical areas: peninsular Spain (Zazo, 1999; Zazo *et al.*, 1997, 2003), Central Italy (Riccio *et al.*, 1999), Tunisia (Jedoui *et al.*, 2003), Bermuda and Bahamas Islands (Chen *et al.*, 1991; Neumann & Hearty, 1996; Hearty, 1998), Western Australia (Zhu *et al.*, 1993), and the Seychelles Islands (Israelson & Wohlfarth, 1999). Evidence of a sudden and short-lived chill during MIS 5e (at about 122 ka BP) has also been reported by Maslin & Tzedakis (1996). From the POS data it seems that MIS $5e_1$ high sea stand have occurred at an elevation slightly higher than the MIS $5e_2$ (Table II, Figure 7), as also indicated by Hillaire-Marcel *et al.* (1996). It is important to note that, to date, the low stand within MIS 5e is only documented by means of two samples from the same cave; thus, additional data are required in order to fully document the presence of this low stand in the POS record.

A low stand episode correlated to MIS 5d has been recognized in Mallorca at –13.5 m ASL around 107.4 ka BP. Another stand at a lesser depth (–10.5 m) follows at about 100 ka BP. This can tentatively be attributed to MIS 5c, which in Eleuthera Island (Bahamas) was also correlated to deposits located at about –15 m ASL (Hearty, 1998). At the same time, Zazo (1999) reports deposits in the Barbados and Bermuda credited to be MIS 5c that are now located below present sea level. It is essential to remark that in Vesica *et al*. (2000) the sample DI-D3 –now dated at 114.2 ± 0.9 ka BP– was not unequivocally assigned to the late MIS 5e, being then attributed to MIS 5c on the basis of an alpha-counting age of 107.9 ± 5.7 ka BP.

The low stand referred here to MIS 5b appears to be the longest of MIS 5 and also at the greatest depth (at least –20.5 m ASL). During the substage MIS 5b, Rose *et al.* (1999) reported mean annual temperatures in Mallorca in the order of 10.8-6.7ºC, generally lower than those estimated during the low stand episode recognized within MIS 5e that is up to 11.3ºC. The probable mean duration of this episode could be around 12.3 ka, from about 97.7 to 85.4 ka BP. The interpretation of sea level changes over this time period is not unequivocal, but it appears that sea level never rose above –17 m ASL.

During MIS 5a strong evidence points toward a relatively short-lived high stand at +1.3/+1.9 m ASL. Ages calculated in Tuccimei *et al.* (2006) are in the range 84.2 to 82.3 ka BP, but recent dates published by Dorale *et al.* (2010) cluster around 81 ka BP. Finally, the sea level recorded at the MIS 5a/MIS 4 boundary is situated –16 m ASL and chronologically corresponds to 78 ka BP.

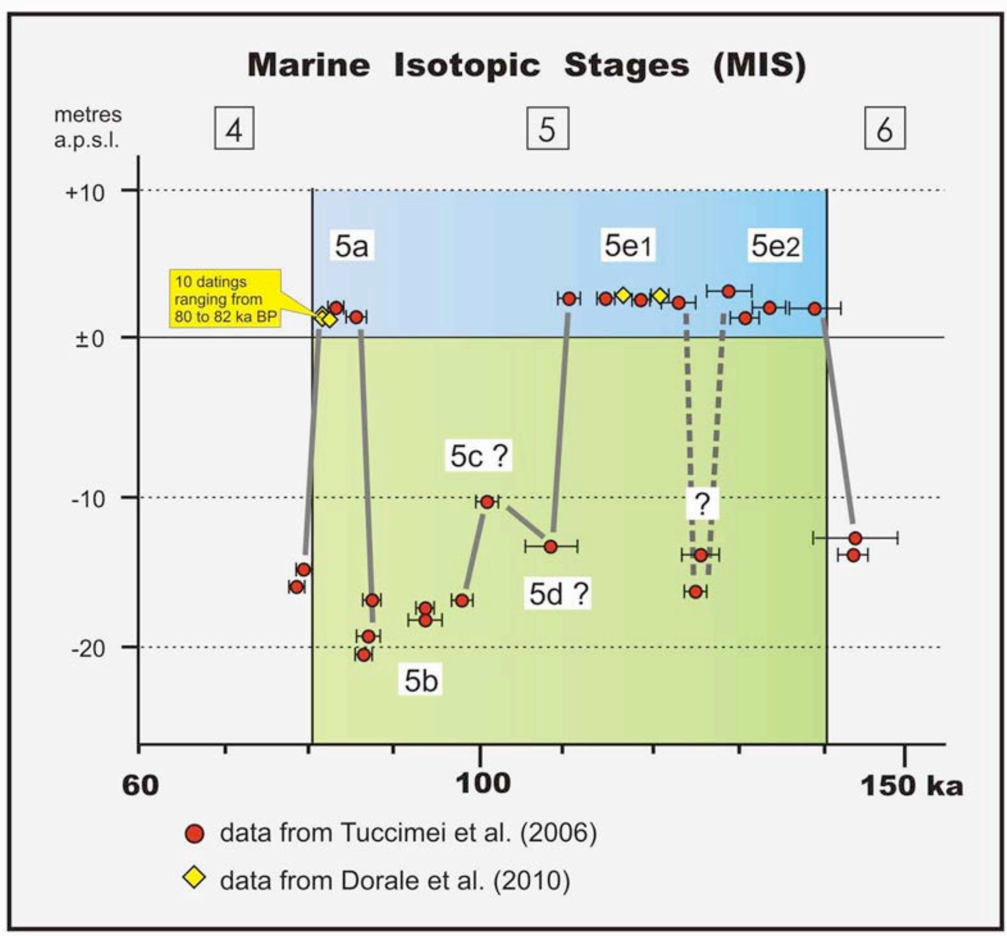


Figure 7. Eustatic curve during MIS 5 deduced on the basis of U/Th ages of Phreatic Overgrowths on Speleothems (POS) from Mallorca Island. Errors are quoted as 2 σ.

Some of the results from POS dating, in particular those concerning the sea level drop near 125 ka BP and the high sea stand during stage MIS 5a, contrast with most of those derived from oxygen isotopic composition of oceanic benthic foraminifera (Imbrie *et al.*, 1984; Martinson *et al.*, 1987). Benthic curves do not typically match sea level estimates due to global causes like variations in deep water temperature or salinity (Chappel & Shackleton, 1986; Shackleton, 1987; Rohling & Bigg, 1998) or in the composition of melted ice (Clarke *et al.*, 2002). Moreover, the oscillations of relative sea level recorded in the Spanish Mediterranean coasts depend on regional influences (Goy *et al.*, 2003), acting superimposed to the global factors, like changes in the influx of Atlantic superficial waters, fluctuations of the North Atlantic Oscillation (NAO), variations of solar activity, as well as different crustal responses to isostatic adjustments. Therefore, estimates of sea level based on benthic foraminifera are somehow problematic in the Western Mediterranean basin, being more straightforward using the direct record of past sea levels supported by local stratigraphic, geomorphological, and paleontological evidence.

The particularities of our proposed eustatic curve must be discussed in comparison with other curves published for Mallorca Island (Butzer & Cuerda, 1962; Butzer, 1975; Cuerda, 1975; Pomar & Cuerda, 1979; Hearty *et al.*, 1986; Hearty, 1987). With respect to the Neothyrrenian (MIS 5a) transgressive peak, no relevant discrepancies occur. However, for the Euthyrrenian (MIS 5e), major differences can be noted. In particular, Cuerda (1975) and Butzer (1975) report Euthyrrenian marine levels up to +11/+14 m ASL, but no evidences of sea levels higher than +2.5/+3 m ASL during MIS 5 have been found in the course of our investigations. This can only be explained if the duration ascribed to the Euthyrrenian by Cuerda (1975) and Butzer (1975) is taken into account. These authors consider that the Euthyrrenian period lasted from 230 to 100 ka BP, so including MIS 7. Over this time period (namely, the penultimate interglacial), only one high stand has been recorded in POS at +5/+6 m ASL, about 232 ka BP (Ginés, 2000; Vesica *et al.*, 2000).

5.2.4. Additional considerations on MIS 5a high stand

Recently, new insights on the ~81 ka BP high stand (MIS 5a) recorded in Mallorca have been provided by Dorale *et al.* (2010). These authors study POS encrustations collected from +1.3 to +1.6 m ASL in five different caves of southern and eastern coasts of the island, obtaining TIMS U/Th ages ranging from 82.0 to 80.1 ka BP. These geochronological data undoubtedly confirm the existence of a sea-level stand higher than the current one during MIS 5a, as was previously recognized by Tuccimei *et al.* (2006). Therefore, Dorale *et al.* (2010) have elaborated on an alternative view that argues that this substage was as ice-free as the present, challenging the conventional view of MIS 5 sea level history and certain facets of ice-age theory.

If interpreted solely as a change in ice-equivalent sea level, the presence of MIS 5a POS at an elevation >1 m ASL conflicts with reconstructions based on raised coral reefs from uplifting coasts as Barbados or New Guinea (Gallup *et al.*, 1994; Lambeck & Chappell, 2001). However, the relative sea level changes at a given site reflect not only changes in global ice volume but also the response of Earth to changes in surface loading in the form of surface deformation and geoid changes (Lambeck & Chappell, 2001; Mitrovica & Milne, 2002), as well as local Global Isostatic Adjustment (GIA). The Mediterranean Sea is an intermediate-field basin, moderately distant from former major glaciation centers. Thus, the +1.5 m high stand at 81 ka BP in Mallorca may plausibly contain a significant effect of GIA, associated to Northern Hemisphere ice sheet history. But, in this respect, Dorale *et al.* (2010) propose that the GIA effects have been overestimated for this region, suggesting the possibility that Mallorca occupies a narrow transition zone between regions of emergence and submergence in the Mediterranean Basin, where sea level nearly follows the eustatic curve. This point of view was recently substantiated by Tuccimei *et al.* (2012).

From the data on Mallorcan POS supplied by Tuccimei *et al.* (2006), Onac *et al.* (2006), Hodge *et al.* (2008), and Dorale *et al.* (2010), it seems well-constrained that MIS 5a sea level high stand involved a very rapid ice melting leading up to this event, which had an estimated duration of maximum 4 ka, from 84 to 80 ka BP. The rates of sea level change were very fast, being comparable to the meltwater pulses of the last major deglaciation (Edwards *et al.*, 1993).

The simple interpretation of these data implies that an eustatic high stand during MIS 5a occurred at 1.3-1.6 m above present sea level. This notion implies less ice on Earth 81 ka ago than today. Furthermore, the suggestion that MIS 5a sea level was slightly higher than present, and only slightly lower than the MIS 5e sea level, implies that most of the ice built up during MIS 5b would have melted during the onset of MIS 5a. The 84 to 80 ka timing of this high stand closely match the June 60ºN insolation peak at 84 ka BP, a pattern consistent with the Milankovitch model. The data from Mallorca –and from other sites around the world– gives solid support to the existence of a high stand at ~81 ka BP; if this is true, the 100 ka cycle so universally accepted as the main rhythm of the Middle and Late Quaternary glaciations, in fact, applies rather poorly to ice growth and decay, but much better to carbon dioxide, methane, and temperatures recorded by polar ice (Toggweiler, 2008).

5.2.5. Patterns of sea level changes in Mallorca during MIS 5

The availability of samples of submerged POS provides new data regarding low sea stands during the Upper Pleistocene, a poorly documented aspect of the sea level history in the Western Mediterranean. It is also feasible to determine some new information on the pattern and rates of sea level change, based on U-series ages performed on the POS alignments supporting the eustatic curve discussed in this paper.

Sea level fluctuations during the Last Interglacial seem to occur in the following pattern: periods of sea stands (long enough to allow the formation of POS at a given elevation) alternate with rapid sea level changes (positive and negative), greater than 18 m in amplitude, occurring within intervals shorter than 5 ka. An approximation of the duration of sea stand episodes can be deduced from the above referred dates of Holocene POS (Tuccimei *et al*., 2010), now growing at the present sea level in numerous littoral caves of the island; these U-series age determinations suggest that at least more than 1 ka of sea level stabilization may be necessary for the formation of a significant POS encrustation. It is worth reminding the reader that the duration of the high stands $5e_2$ and $5e_1$ has been estimated on the order of 10 ka, on the basis of several high precision dates (Tuccimei *et al*., 2006). This is consistent with an extended time of climatic stability during MIS 5e (136 to 124 ka BP), as also shown in the Devils Hole record by Winograd *et al*. (1997) in southwestern North America, partly overlapping with the episode here attributed to MIS $5e_2$.

The rates of sea level changes that can be deduced from our data range from a minimum of 2.9 mm/year to a maximum of 20 mm/year, with average figures of 5.9 mm/year (Tuccimei *et al*., 2006; Dorale *et al*., 2010). These values have been inferred by taking into account the age calculated for each sample, without considering the quoted errors of the datings. The sea level drop that occurred during MIS 5e was presumably very fast; especially rapid was the rising trend associated with the onset of MIS $5e_1$. In the same manner, the rise from MIS 5b to MIS 5a happened at the highest rate (>8 mm/year) throughout MIS 5. Such tendencies agree with quicker sea level shifts during transgressions as discussed by Harmon (1980). In general terms, the obtained rates are similar to those calculated by Harmon (1985) in Bermuda Islands, 3.5-6.0 mm/year.

5.2.6. Incidence of local tectonics

The eastern littoral area of Mallorca has proven to be suitable for sea-level change studies because it is considered tectonically stable, although affected by some recent minor tectonic activity. U-series dating of emerged POS demonstrated a maximum of 1 m vertical displacement among encrustations formed during MIS 5e and 5a in several caves (Fornós *et al.*, 2002). These authors have discussed the slightly different elevations of coeval POS samples, in light of other regional geomorphological, structural, and stratigraphical evidence. This approach has outlined a general tectonic tilting of the eastern part of Mallorca, with a maximum displacement of 1.5 m, which results in progressive lowering of the southern end of the island. The proposed tilting has occurred, at least partially, after MIS 5a, because the deposits of that age also seem to be affected. The rate of tectonic lowering was evaluated at 0.02 mm/year (Fornós *et al.*, 2002).

These small tectonic disturbances can be considered negligible with respect to the fluctuation amplitudes existing between the high and low stands recorded in the studied caves; therefore, the Mallorcan POS arise as valuable and accurate proxies of sea level in the Western Mediterranean basin, at least during Holocene and Upper Pleistocene times. Within this context, and taking into account the fact that MIS 5e POS deposits are located at a mean height of +2 m ASL –hence, not substantially uplifted by tectonic movements–, the presence of MIS 5a encrustations between +1.3 and +1.9 m ASL, clearly indicate a sea stand higher than the current one that is not, by any means, the result of tectonic uplifting of deposits precipitated at lower elevations. In other words, it is implausible that MIS 5a deposits could have been significantly elevated by tectonics while MIS 5e deposits were not.

6. Additional chronological approaches

Recently, additional studies were directed towards the ^{14}C dating of Holocene POS. The aim of these investigations was to compare the ^{14}C and U/Th ages previously obtained and determine whether incorporation of dead carbon inherited from the dissolution of ^{14}C-free limestone poses any problems. Generally speaking, the ^{14}C ages are consistent with those generated by U/Th dating (Tuccimei *et al.*, 2011), although some of the results prove to be site dependent and linked to the local residence time of waters. In the case of Cova de Cala Varques samples, ^{14}C and U/Th ages are coincident within the error range (2.8 to 1.1 ka and 2.8 to 0.3 ka BP, respectively). In Cova des Pas de Vallgornera, ^{14}C ages are steadily 2.3-2.4 ka older that the U/Th data (4.1 to 3.0 ka vs. 1.8 to 0.6 ka BP) a fact that was linked to higher values (~25%) of dead carbon estimated for these samples. Nevertheless, the constant differences between the two data sets and the fairly constant $\delta^{13}C$ values of the speleothem (around -5‰ VPDB) suggest that the system was stable over the entire growth period of the phreatic encrustation. It seems that the use of radiocarbon dating in POS geochronological studies is promising, but in some situations might be problematic due to the so-called reservoir effect. Obviously, its use is restricted to the investigation of Last Glaciation and post-glacial samples.

During the 1980s, attempts were made to apply ESR dating techniques to the study of Pleistocene POS from Mallorca. These investigations were focused on the very complex record existing in Cova de sa Bassa Blanca (Alcúdia), where an extensive sampling campaign was completed in 1981 including the extraction of 25 horizontal drill-cores from the walls of the cave (Maroto & Font, 1981; HADES, 1985). The ESR measurements were conducted by Grün (1985, 1986) on the 190 cm long core SBB/S21, collected 8 m above present-day sea level. This author proposed that the analyzed sequence of carbonate precipitates –mostly phreatic in origin, but also showing alternate layers of vadose flowstone– covers a time span ranging from 700 to 200 ka BP, hence going back from the earlier times of the Middle Pleistocene to the MIS 7. Some U/Th ages were also obtained in order to constrain the chronology of the core; these investigations concluded that the deposition of the outer part of the sequence took place during the penultimate interglaciation.

In this collaborative research carried out in the 80s with G.J. Hennig, eight different samples were measured (Ginés, 2000) ranging from the Holocene encrustations of Cova de Cala Varques A to some Middle Pleistocene POS from caves in the northeastern coasts of Mallorca. The results were inconsistent in general, except for the postglacial sample from Cova de Cala Varques A (accumulated dose <1 krad). Most of the measured samples yielded accumulated doses in the range of 10 to 27 krad, pointing to a Middle Pleistocene chronology (MIS 7 to 11, presumably), which is not contradictory with the scarce and inaccurate U/Th data available on the same samples (Hennig *et al.*, 1981; Ginés & Ginés, 1989, 1993a). Particularly inconsistent are the ESR measurements of two samples from Coves Petites, collected at elevations of +30 and +40 m ASL, but with very low accumulated doses of 6 and 7 krad respectively; it seems that intense recrystallization processes are responsible for the rejuvenation of these POS, otherwise clearly Middle Pleistocene in age. After an initial enthusiasm in using this geochronological method, scientists are aware about its serious limitations, particularly when computing the annual dose of radiation received by speleothems (Gillieson, 1996; Ford & Williams, 2007).

7. Additional paleoclimatic data

Significant paleoclimatic information is recovered from the rates of sea-level rise and fall discussed previously. A mean rate on the order of 6 m/ka was calculated for sea-level oscillations in Mallorca, linked to the climatic changes documented in our cave records. The obtained values imply that fluctuations of the Mediterranean Sea as high as 20 metres might occur in time spans shorter than 5 ka (Tuccimei *et al.*, 2006; Dorale *et al.*, 2010). In spite of the high rate shown by the fluctuating pattern deduced from our data, the formation of phreatic speleothem paleolevels requires that sea-level is stable long enough to allow the deposition of noticeable crystalline overgrowths. The length of these sea-stands may at least span a few thousands of years, as suggested by Tuccimei *et al.* (2006). The postulated fluctuation-stabilization pattern is further supported by the relatively stable sea-level at least since 2.8 ka BP (Tuccimei *et al.*, 2010, 2011); this steady state sea-level is recorded by a spectacular decimeter-size thick POS. Therefore, the deposition of similar bulky crystallization paleolevels (both at higher or/and lower elevations) requires the existence of some stable sea-stands, related to relatively even climatic conditions that were stepping the fluctuating trend exposed in Figure 7.

The data on MIS 5 and 4 recovered from Mallorca's POS clearly show a complex series of dramatic paleoenvironmental changes, related to extreme climate shifts happened during the time interval 150 to 60 ka BP. The magnitude of thermal variations over this time period (Muller & MacDonald, 2000) is undoubtedly large enough to explain, in a satisfactory manner, sea-level decreases of at least 20 metres like those documented in the littoral caves of the island. In this sense, Rose *et al.* (1999) presented differences as high as 11ºC between the mean temperatures calculated for the thermal maxima and minima across the entire MIS 5 in Mallorca. Furthermore, one cannot exclude the possibility that during some of the cold events documented in our record –particularly, MIS 5b and 4– regressive pulses could have been even greater than the ones predicted through our studies.

A limited number of oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) stable isotope analyses were performed on phreatic speleothems corresponding to transgressive peaks (Figure 8). The values obtained from the growing bands of some samples belonging to MIS 5, show an isotopic evolution towards heavier compositions through the warm substages 5a and 5e. Vesica *et al*. (2000) explain this trend as a result of excessive marine water intrusion in the geochemical system of the cave ponds, linked to increasing aridity.

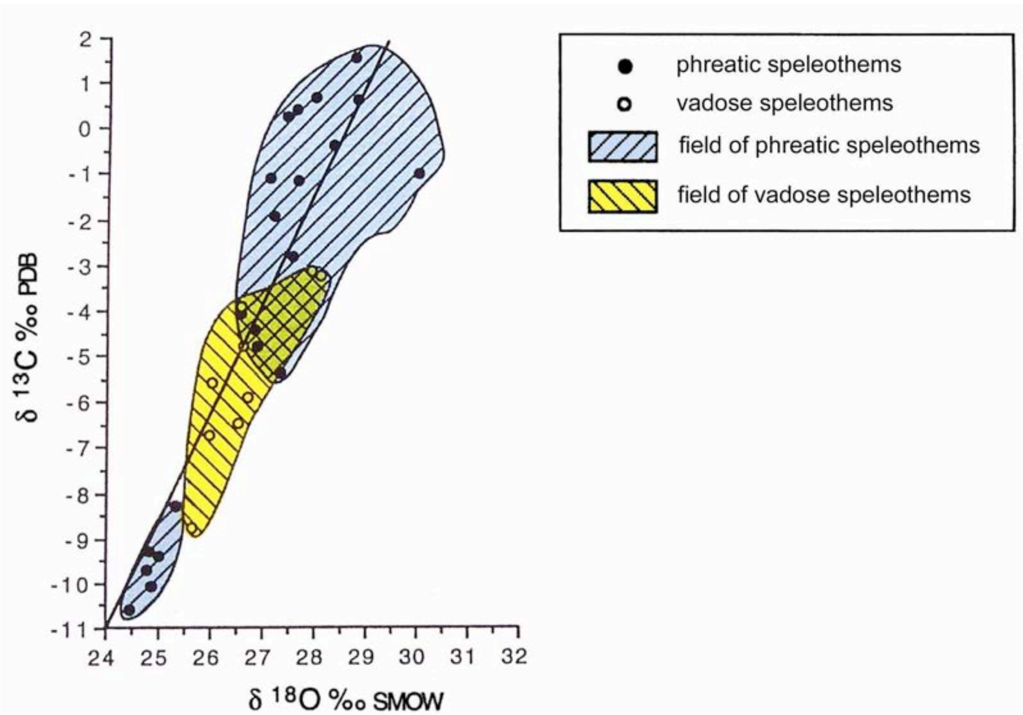


Figure 8. Some data on stable isotopes: $\delta^{18}O$ vs. $\delta^{13}C$ of different kinds of speleothems and their relative fields (from Vesica *et al*., 2000). The correlation coefficient of the regression line is 0.89.

Similarly, Durán & López (1999) also found climatic evidence of notable aridity during MIS 5, whereas in the next cold stage (MIS 4) there are reliable evidences of a significant hydrological activity (increase of precipitation) over the endokarstic systems from southern Spain. These paleoclimatic interpretations may surface some controversy on the usual assumption that –in this geographical area– the interglacial periods correlate with events of high rainfall rates (Cuerda, 1975; Rose *et al*., 1999). The fact we have not been able, until today, to perform stable isotope analyses on POS samples collected below the current sea-level, hinders the possibility of attaining additional information on the environmental depositional conditions that prevailed during the Upper Pleistocene cold events.

Finally, it must be mentioned the study of Csoma *et al*. (2006) on a 122 cm long core (SBB/S24) drilled out from the walls of Cova de sa Bassa Blanca, 8 m above the current sea level. The complex sequence hosted by this cave includes episodes of phreatic aragonite precipitation alternating with phases of vadose flowstone deposition. Stable isotope analyses conducted on vadose speleothems show a slight increase of the $\delta^{18}O$ and $\delta^{13}C$ towards higher values, which indicate their deposition during cold climate events when seawater $\delta^{18}O$ became more positive. Concerning the phreatic precipitates, it appears that local geochemical conditions (CO_2 degassing, depth below the water table, etc.) are the main controls on their stable isotope values, rather than the linear mixing between meteoric and marine end-members. Csoma *et al.* (2006) attributed the presence of aragonite in the phreatic deposits to episodes characterized by a reduced meteoric recharge during different interglacial stages.

8. Mineralogical and crystallographic aspects

The petrology, mineralogy, and crystallography of POS are topics still not investigated in depth. Nevertheless, some pioneering contributions more or less extensive and detailed were published a few decades ago (Pomar *et al*., 1976, 1979; Ginés *et al*., 1981b; HADES, 1985). Furthermore, some recent studies have been published on the Middle Pleistocene deposits from Cova de Sa Bassa Blanca (Csoma *et al*., 2006) as well as on Upper Pleistocene crystallizations from different caves of eastern Mallorca (Ginés, 2000; Ginés *et al*., 2005). The mineralogical, textural, and crystallographical aspects of POS, based on samples used for our geochronological investigations are presented in the paragraphs below.

8.1. Mineralogy

The mineralogy of different growth layers corresponding to 13 phreatic speleothems was determined by XRD semiquantitative techniques (Ginés *et al*., 2005). From each POS specimen, two to five sub-samples were recovered, depending on the complexity of the speleothem and the thickness of the phreatic overgrowth; all analyzed samples were collected from the phreatic encrustation, whereas the vadose support of these crystallizations were not sampled.

The mineralogical data are assembled in Table IV, along with the U/Th ages of the samples and the geological setting from each cave. Calcite is the dominant phase, in particular high-Mg calcite (HMC) whose magnesium content is comprised between 4 and 11%. Only a few samples are composed of low-Mg calcite (LMC) or by HMC calcite with Mg values higher than 11%. The second more frequent mineral is aragonite (a $CaCO_3$ polymorph) that exceeds 70% in several samples.

Dolomite –$CaMg(CO_3)_2$– is always irrelevant from a quantitative point of view (<5%), although in two samples, it reaches values higher than 10%. Its presence could be related, in all cases, to the dolomitic character of the cave hosting rocks. Quartz has been detected (<5%) exclusively in the outer layer of one speleothem, therefore linked probably to an exogene source.

Considering the POS ages, one can note that the aragonite crystallizations were formed only in different MIS 5 high sea stands. This fact could support the paleoclimatic significance of aragonitic mineralogy, which would be linked to warmer periods (Pomar *et al.*, 1976; Ginés *et al.*, 1981; HADES, 1985; Ginés, 2000; Vesica *et al.*, 2000).

Although the mineralogical variability in the marine carbonates as a consequence of different water temperatures is well documented (Mitsuguchi *et al.*, 1996; Marshall & McCulloch, 2002), the real situation in the littoral cave environments appears to be much more complex (Ginés, 2000). It is therefore, necessary to take into account that among the investigated speleothems corresponding to MIS 5 there are abundant deposits of calcite, a fact that does not support the existence of an unambiguous causal relationship between aragonite precipitation and interglacial thermal maximum. Within this context, Rao (1996) and Hill & Forti (1997) highlighted the participation of many different factors –in addition to high temperatures– which control the deposition of aragonite in the subterranean environment: Mg and Sr content of waters, saturation of the solutions, evaporation processes, pCO_2, salinity, concentration of Ca, etc. Following this argument, it is feasible to consider the effect of other variables, potentially related to climate, which control the kinetics of aragonite deposition; for example, low Mg/Ca ratios in the solutions favor the precipitation of calcite, whereas Mg/Ca ratios higher than 4.4 cause the deposition of aragonite (Folk, 1974; Hill & Forti, 1997). Consequently, the presence of this mineral could identify important information on sea water intrusion (high ratio Mg/Ca) that could be related to periods of marked aridity. In conclusion, the precipitation of aragonite during MIS 5 should be perceived as a potential paleoclimatic indicator, regardless the mechanism controlling its deposition (i.e., relatively high mean temperature or significant saltwater intrusion associated with low rainfall; Vesica *et al.*, 2000).

8.2. Crystallography

The description of the samples included in Table IV was undertaken in order to propose a classification (Figure 9) that attempts to relate the crystallographical aspects the mineralogy and morphology of the phreatic speleothems. As a general observation we note that the crystals size making up the POS tend to be equant and they appear relatively homogeneous in successive depositional bands. In certain cases, inequicrystalline aggregates are observed, often involving superimposed micrometric-size calcite crystals on fibro-radial acicular aragonite crystals whose size is millimetric to centimetric (Figure 10a).

Table IV. Mineralogical semi-quantitative data corresponding to POS samples collected in littoral caves of Mallorca (data from Ginés *et al.*, 2005). VB: Cova de Cala Varques B; FA: Cova de Cala Falcó; DI: Cova del Dimoni; SE: Cova des Serral; PI: Coves del Pirata; PO: Cova des Pont; all of them in Manacor municipality. BA: Cova de na Barxa; MI: Cova de na Mitjana; both in Capdepera municipality. a: outer subsample; b - e: subsamples obtained sequentially towards the inner part of the speleothem.

Sample		Calcite			Aragonite	Dolomite	Quartz	*MIS*	*Geological setting*
		LMC < 4% Mg	HMC 4-11% Mg	HMC >11% Mg					
VB-SA	**a**	—	100.00	—	—	—	—		
	b	—	100.00	—	—	—	—	1	**m**
	c	—	100.00	—	—	—	—		
VB-D2	**a**	—	100.00	—	—	—	—		
	b	—	100.00	—	—	—	—		
	c	—	100.00	—	—	—	—	5a	**m**
	d	—	100.00	—	—	—	—		
	e	—	100.00	—	—	—	—		
FA-D3-4	**a**	—	23.85	60.18	2.62	13.35	—		
	b	—	11.73	—	85.64	2.63	—	5a	**m**
	c	—	12.68	—	82.32	5.00	—		
DI-D3	**a**	—	—	—	98.00	2.00	—		
	b	—	53.59	—	45.61	0.80	—	5e	**m**
	c	—	1.88	—	94.77	3.35	—		
	d	—	25.95	—	74.05	—	—		
DI-D1-1	**a**	—	28.03	—	68.71	3.26	—		
	b	—	44.48	—	54.12	1.40	—	5e	**m**
	c	—	74.74	—	25.26	—	—		
SE-D2	**a**	—	100.00	—	—	—	—		
	b	—	100.00	—	—	—	—	5e	**m**
	c	—	100.00	—	—	—	—		
PI-D1	**a**	—	100.00	—	—	—	—	5e	**m**
	b	—	100.00	—	—	—	—		
PO-D2	**a**	—	100.00	—	—	—	—	5e	**m**
	b	100.00	—	—	—	—	—		
BA-D3	**a**	63,44	—	—	34.92	1.64	—		
	b	—	—	90.76	1.30	7.94	—	5e	**Mz**
	c #	—	95.50	—	—	4.50	—		
	d	—	—	81.60	—	18.40	—		
MI-D1	**a**	—	100.00	—	—	—	—		
	b	—	100.00	—	—	—	—	7 ?	**Mz**
	c	—	100.00	—	—	—	—		
	d	—	100.00	—	—	—	—		
MI-D2	**a**	—	100.00	—	—	—	—		
	b	—	100.00	—	—	—	—	7 ?	**Mz**
	c	—	100.00	—	—	—	—		
MI-D3	**a**	—	100.00	—	—	—	—		
	b	—	100.00	—	—	—	—	9 ?	**Mz**
	c	—	100.00	—	—	—	—		
DI-D4	**a**	—	41.02	52.62	1.02	0.46	4.88		
	b	—	100.00	—	—	—	—	without dating	**m**
	c	—	100.00	—	—	—	—		

traces of clay minerals

m Upper Miocene calcarenites **Mz** Mesozoic limestones

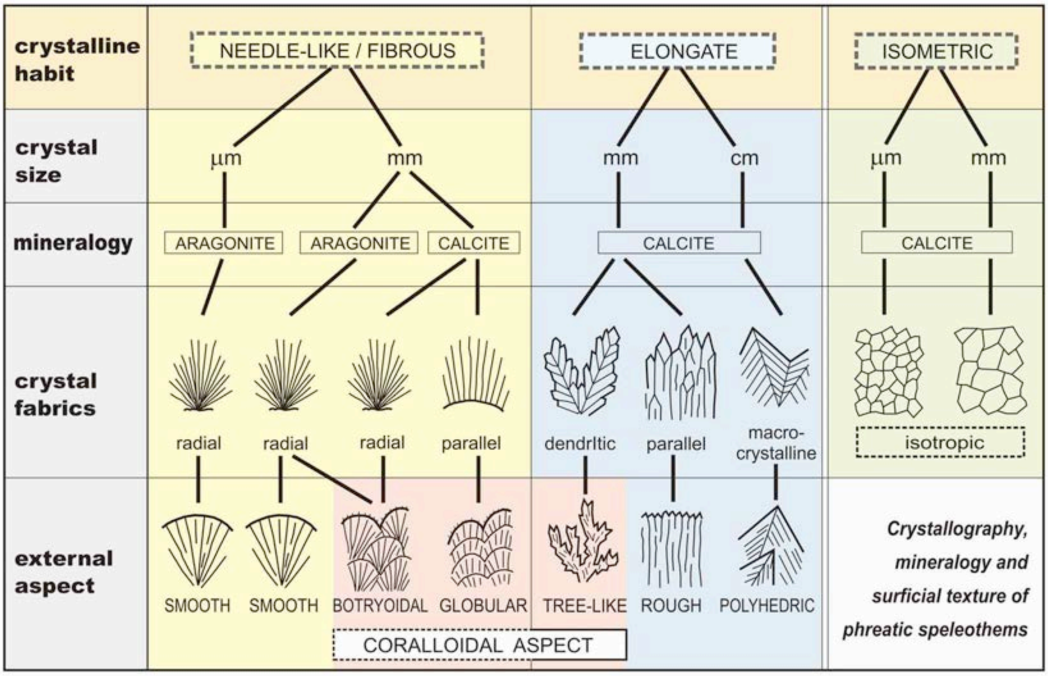
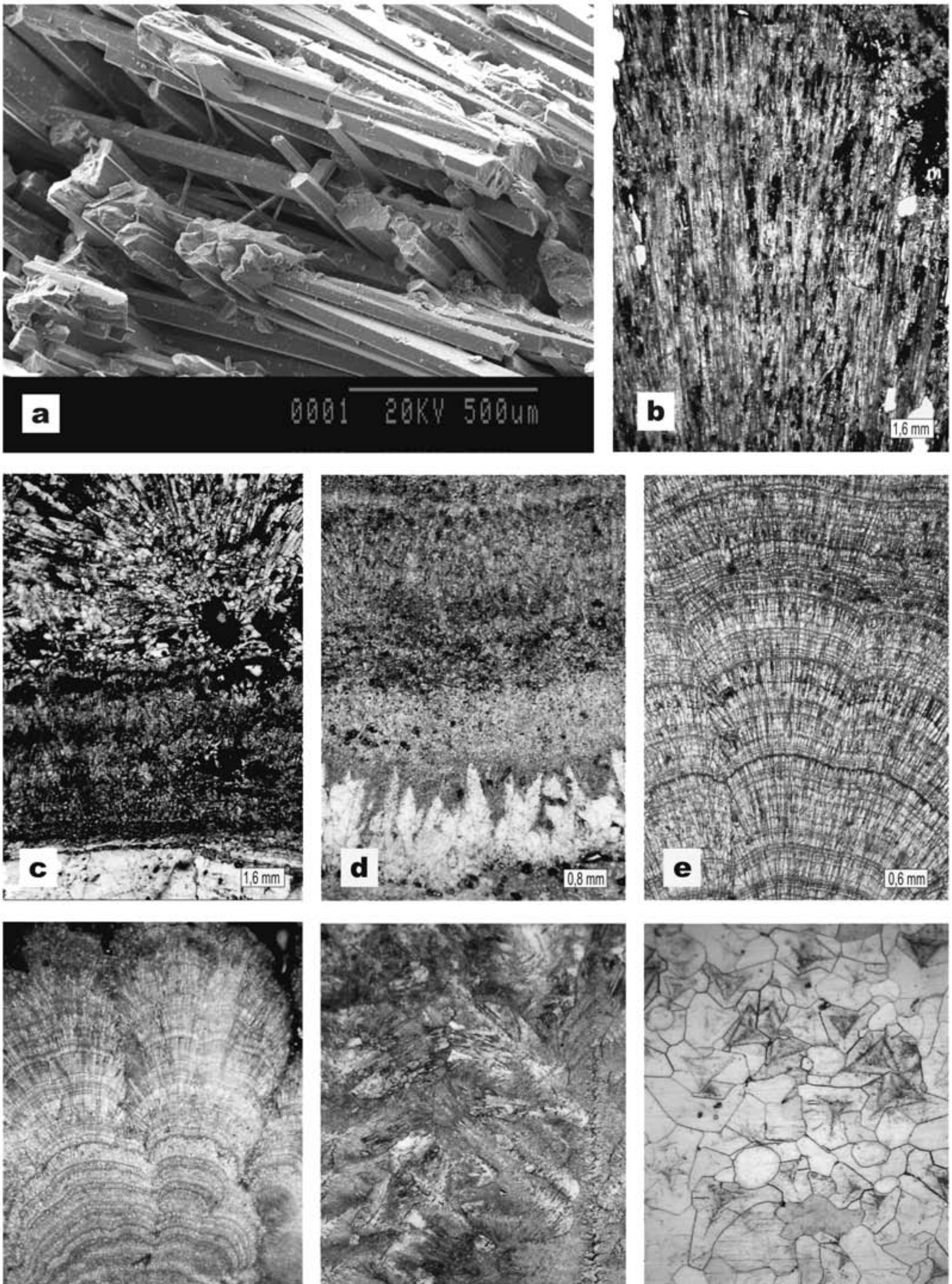


Figure 9. Synthesis of the results obtained from some textural researches about phreatic crystallizations of Mallorcan caves (according to Ginés *et al.*, 2005).

Both with naked eyes and under the microscope, it is always possible to observe the radial-fibrous/acicular fabric of aragonite speleothems (Figure 10b). This fabric is the result of the aragonite crystals arrangement around the inner vadose support (upper part of Figures 10c and 10d). The resulting external morphologies of aragonite POS are rounded and smooth, yielding in some cases encrustations that are rather botryoidal, due to the fibro-radial aggregates of millimetric crystals that often constitute hemispheric bumps. On the other hand, crystallizations made up of calcite fall roughly into three main habits: fibrous, elongated, and isometric (Figure 9). The first two habits produce fabrics related to the competitive growth of crystals, which takes place whenever the growth vector is perpendicular to the substrate (Chafetz *et al.*, 1985, González *et al.*, 1992).

Figure 10. (next page) Microphotographs of some POS samples (after Ginés et al., 2005). a: SEM image of an aragonitic sample from Cova des Pas de Vallgornera (Llucmajor); b, c: radial aggregates of needle-like aragonite crystals (sample DI-D4; Cova del Dimoni, Manacor); d: micrometric calcite crystals covered with successive layers of aragonite needles (sample FA-D3-4; Cova de Cala Falcó, Manacor); e, f: fibrous calcite crystals forming aggregates of parallel fabrics and globular morphology (sample VB-SA; Cova de Cala Varques B, Manacor); g: elongate calcite macrocrystals that build up speleothems with a polyhedric surface (sample MI-D2; Cova de na Mitjana, Capdepera); h: millimetric crystals of isotropic calcite, corresponding to the inner layers of a phreatic overgrowth (sample PO-D2; Cova des Pont, Manacor).


a
0001 20KV 500um
b
1,6 mm
c
1,6 mm
d
0,8 mm
e
0,6 mm
f
1,6 mm
g
1,6 mm
h
1,6 mm

The fibrous calcites, with small crystals of millimetric size, produce two kinds of fabrics: radial and parallel. The radial fabrics are entirely similar to those observed in the crystallizations of aragonite, consisting of bundles of fibrous crystals growing divergent from specific points of nucleation. The parallel fabrics (Figure 10e) show a growth pattern perpendicular to the support or substrate, pattern that in the outer layer of the speleothem can generate structures morphologically similar to radial aggregates (Figure 10f). The external appearance of the two fabrics often converges, resulting in rounded protuberances of globular or botryoidal aspect whose sizes are centimetric.

The calcite deposits arranged in aggregates of large elongated crystals, with sizes millimetric to centimetric (see Figure 9), creates three basic types of fabrics: dendritic, parallel, and macrocrystalline. On the one hand, large rhombohedric euhedral crystals are organized in fabrics that build up speleothems of branching structure and dendritic appearance. This class of deposits resembles the coralloid speleothems described by Hill & Forti (1997) in a broad sense, although the globular and botryoidal morphologies, related to fibrous crystalline habits, can also resemble coralloids in the most extreme cases of their development. Secondly, there are parallel calcite fabrics which result in rounded and bulky speleothems, but with an uneven surface due to the small faceted crystals macroscopically observable on its outside part. Finally, it is worth mentioning the spectacular overgrowths whose external morphology display striking polyhedric facets due to the calcite macrocrystals on millimetric to centimetric scales (Figure 10g).

The isometric calcite crystallizations seem to be limited to equicrystalline aggregates (Figure 10h). They only occur in the early growth bands of the phreatic speleothems and are associated with abundant nucleation points.

The broad crystallographic variability observed (Figures 5 and 10) involves a complex web of physical and chemical parameters –temperature, pCO_2, saturation index, Mg^{2+} content, water movement, etc– that control the mineralogy and size of precipitated crystals, as well as their growth rates (Folk, 1974; Giménez & Taberner, 1997; Schneidermann & Harris, 1985). Therefore, much more studies need to be carried out in order to shed light on this aspect of POS.

9. Conclusions: state-of-the-art and future perspectives

The time span elapsed since the beginning of our studies on POS of Mallorcan caves –about 40 years– allowed us to gain a proper perspective on the geochronological relevance and possible limitations concerning this particular record of the sea level history. Based on a remarkable set of geomorphological and U/Th data produced since 1972, today is possible to emphasize the reliability of this special proxy for Quaternary sea-level reconstruction. The radiometric dating programmes confirmed the Holocene age for the POS deposited around the current sea level (Tuccimei *et al.,* 2010, 2011), as well as the general stratigraphic consistency of the U/Th dates on all the other samples covering the Upper Pleistocene (Tuccimei *et al.*, 2006).

The analytical results also pointed out the possibility that neomorphic processes affecting the POS might be responsible for some of the inconsistent ages obtained by means of U/Th dating method. In this respect, the recrystallization processes that affect certain speleothems are relatively more frequent among the samples that are older; especially those of Middle Pleistocene age (Ginés, 2000).

To the above-mentioned problems, post-depositional diagenesis of the isotopic content of some POS samples also need to be considered. These processes seem to be relatively common for most of the speleothems collected below the present sea level (i.e., corresponding to regressive events). It seems reasonable to predict that the prolonged and repeated immersion of these POS in the coastal mixing zone caused, in some cases, the partial dissolution of these deposits (i.e., open geochemical system), triggering all the dating problems that this process entails. To minimize such problems, several age determinations were conducted on each speleothem. Doing so, the lack of samples out of stratigraphic order confirmed that the geochemical system remained closed.

Regarding the paleoclimatic data that POS can provide, it is necessary to recognize some important limitations related to the fragmentary nature of this record. This is because both in time and space, each marine sea-stand is only documented by the period of stabilization of the coastal water table at a given elevation. Obviously, this means that there is not a continuous record of POS over the last 500 ka. Therefore, stable isotope data obtained are scarce and poorly illustrative. However, this does not diminish the possibility of obtaining detailed paleoclimatic data, particularly in what concerns specific geochronological events such as the Holocene sea level or the high sea stands related to the Last Interglacial, for instance.

So far, the geomorphological and chronological data set accumulated during the last four decades, has allowed the reconstruction of a fairly detailed eustatic curve in the Western Mediterranean basin for the time span between 150 and 60 ka BP (Tuccimei *et al.*, 2006). This curve highlights the existence of a high sea level stand ~81 ka ago, during MIS 5a (Dorale *et al.*, 2010), a finding that is criticized by some scientists, because GIA was not used to reconcile this high stand.

In the current state of knowledge, it becomes increasingly clear that the study of coastal phreatic speleothems (POS) constitutes a new tool with established validity for the study of sea level history in limestone coastal areas. This particular kind of speleothem encrustations favorably complements the conventional littoral records (beaches, ancient shorelines, coastal fossil deposits, etc.), providing even more accurate data on the elevation of the coastlines and the magnitude of tidal fluctuation. In addition, the geographic setting (karst caves) of this type of phreatic crystallizations protects them against dynamics that marine erosion imposes to the evolution of the coastline. Undoubtedly, the data supplied by the POS deposits existing in coastal caves from other parts of the world could contribute important data to the global sea level history, effectively complementing other proxy records. With over one third of the world's population living within coastline regions, understanding the history and future impacts of global sea-level change ranks as a top priority in the Earth Sciences.

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